Published in final edited form as:
Stroke. 2014 December ; 45(12): 3734–3741. doi:10.1161/STROKEAHA.114.003130.

Ambient Air Pollution and Stroke

Petter L. Ljungman, M.D. Ph. D.[1,2] and **Murray A. Mittleman, M.D. Dr.PH.**[1]

[1]Cardiovascular Epidemiology Research Unit, Cardiovascular Division, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts

[2]Unit of Environmental Epidemiology, Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden

Background

Stroke is a leading cause of death in the US[1] and worldwide (www.who.int) and may lead to considerable neurological sequelae including aphasia, paraplegia and dementia. The estimated health care costs of stroke in the US exceed $36 billion per year[1]. A large body of evidence supports the association between ambient air pollution exposure and increased cardiovascular mortality and morbidity[2], but only recently have several studies specifically demonstrated an association with increased stroke risk.

Major sources of air pollution include traffic, power plants and in developing countries, biomass combustion. Both particles and gases are emitted through combustion. Particulate matter with aerodynamic diameter <10 μm (PM_{10}) include ultrafine particles ($PM_{1.0}$), fine particles ($PM_{2.5}$) and coarse particles ($PM_{10-2.5}$). Ultrafine particles are emitted in fresh exhaust and coalesce into $PM_{2.5}$ within a short time frame. $PM_{2.5}$ includes both local sources from traffic emissions and domestic heating and regional sources from power plants, biogenic emissions and traffic whereas coarse particles are a heterogenous mixture that include road dust, endotoxins, and suspended crustal matter. Carbon monoxide (CO), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2) and ground-level ozone (O_3) are gaseous pollutants emitted as a result of combustion processes. CO is mainly attributed to mobile sources in urban environments and NO_2 and NO_x are rapidly formed in emissions from combustion sources such as traffic and power plants. The main source of SO_2 is from fossil fuel power plants. Ground-level O_3 is formed as a result of atmospheric reactions of NO_2 with hydrocarbons in the presence of sunlight and is a major constituent of photochemical smog. Several of the mentioned pollutants are regulated based on evidence of adverse health effects[3]. Possible mechanistic pathways including induction of oxidative stress, inflammation, atherosclerosis and autonomic dysregulation have been outlined in detail[2–4] and are beyond the scope of the current review.

Corresponding author: Murray A. Mittleman, Cardiovascular Epidemiology Research Unit, Cardiovascular Division, Beth Israel Deaconess Medical Center, 375 Longwood Ave, 4th floor ste 440, Boston, MA 02215-5395, USA, Phone 617-632-7652, Fax 617-632-7698, mmittlema@bidmc.harvard.edu.

Online supplemental tables

Table I. Studies of Short-term Air Pollution Exposure and Stroke Mortality: Detailed estimates.

Table II. Studies of Short-term Air Pollution Exposure and Hospitalization for Stroke: Detailed estimates.

Disclosures: None

This review aims to assess the current evidence regarding the association of air pollution exposure with incidence of ischemic and hemorrhagic stroke considering long-term and short-term exposure to ambient pollutants.

Long-Term Air Pollution Exposure

Most studies of long-term exposure to air pollution and stroke outcomes have used estimates of exposure at residential address in months to years as a proxy for long-term accumulated individual exposure. Exposure has then been assessed using residential distance to major roadways, measurements from closest available fixed monitor or advanced modeling of pollutants combining fixed monitoring measurements with land-use data, emissions databases, traffic density counts and meteorology incorporated into geographical information systems (GIS). These GIS models can also include population-based data such as average income level and average smoking prevalence.

Long-term air pollution exposure and stroke mortality

Studies considering long-term exposure to air pollution and stroke mortality have reported that living in areas with higher ambient pollution is associated with higher risk of stroke mortality (Table 1). Studies from the UK[5, 6] and northwest Florida[7] containing large administrative databases with cause of death, residence, sex and area-based data such as socioeconomic status, urbanization, smoking prevalence and greenness. Living near a main road[5], traffic sources[7], point sources of emissions[7] or higher modeled exposure to PM_{10}, CO and NO_x[6] were all associated with stroke mortality. Several cohort studies have also studied the association between long-term exposure to air pollution and stroke mortality[8–13]. These studies have more detailed individual-level data that improves the ability to adjust for potential confounders that may influence the place of residence and the risk of stroke mortality. Strongest associations were reported in the prospective Womens' Health Initiative cohort[11] that included well-validated outcome assessment. In the Californian residents of the American Cancer Society cohort study[9], associations were reported for NO_2 and any stroke mortality and borderline significant associations for $PM_{2.5}$. In the California Teachers Study[10], however, higher long-term PM_{10} and $PM_{2.5}$ exposure were not associated with cerebrovascular mortality. In 232 rural districts of Japan[12] including 250 stroke deaths, higher long-term PM_{10} exposure was not associated with stroke mortality. Specific characterization of stroke into types and subtypes was available in two studies, in Shizuoka, Japan[13] and in Denmark[8]. Yorifuji et al[13] reported associations between NO_2 and mortality from ischemic stroke and intracerebral hemorrhage but not subarachnoid hemorrhage. Andersen et al[8] reported borderline significant associations between long-term NO_2 exposure and ischemic stroke but not for hemorrhagic strokes and did not further subtype hemorrhagic strokes.

Long-term air pollution exposure and hospitalization for stroke

In studies of long-term exposure to air pollution and hospitalization for stroke, higher exposure at home addresses was also associated with higher risk of admission for stroke in some studies, but results were less consistent than for stroke mortality (Table 2). Most commonly reported pollutants included long-term exposure to PM_{10}[6, 10, 14, 15],

$PM_{2.5}$[10, 11, 16] and NO_x[6, 17, 18] or NO_2[8, 14, 15, 19, 20]. Many of the cohort studies reported positive associations[8, 10, 11, 14, 21] whereas ecological studies[6, 15, 19] and case-control studies[17, 18, 21] showed mixed results. In a random-effects meta-analysis of 11 European cohorts[16], long-term $PM_{2.5}$ was associated more strongly associated with stroke in subjects older than 60 years old, never-smokers and among subjects with exposure levels less than 25 μg/m^3 (current annual mean air quality standard in Europe). Studies that compared long-term air pollution exposure and hospital admissions according to specific stroke type reported positive associations for NO_2, CO and traffic density and admissions for both ischemic and hemorrhagic stroke[19] in Edmonton, Canada whereas NO_2[8, 20] in Denmark or NO_x[15] in London, UK demonstrated associations consistent with ischemic stroke but not hemorrhagic stroke. Two studies from Scania, Sweden[17, 18] only including hospital admissions for ischemic stroke observed associations between higher long-term exposure to NO_x and higher risk of hospital admission for ischemic stroke in participants with diabetes but found no association in the overall population, in smokers, or in participants with hypertension or atrial fibrillation. A recent population-based cohort study in Denmark studying long-term NO_2 and traffic noise exposure and stroke incidence reported positive associations for ischemic stroke in separate analyses for both noise and NO_2 but in combined analyses NO_2 was only associated with fatal ischemic strokes[20].

Short-term Air Pollution Exposure

Day to day differences in air pollution exposure in the days preceding stroke are used to study possible triggering effects of air pollution on stroke. In time-series analyses, daily counts of stroke deaths or admissions are compared with air pollution levels on the same day or preceding days in a study region. In case-crossover analyses exposure levels preceding stroke mortality or hospitalization in an individual are contrasted with control periods within the same calendar month within each individual controlling for season and day of week and perfectly matching time-invariant patient characteristics by design.

A number of studies have investigated associations between short-term exposure to air pollutants including PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2 and O_3 and stroke mortality or hospitalizations for stroke in many cities in North America, Europe and East Asia. Mean levels of pollutants varied considerably between study locations from low polluted cities like Dijon, France (daily mean PM_{10} 20 μg/m^3) to highly polluted cities like Wuhan, China (daily mean PM_{10} 119 μg/m^3).

Short-term air pollution exposure and stroke mortality

A majority of studies investigating short-term exposure to air pollution and stroke mortality have been time-series studies[22–36], the remainder used case-crossover design[37–41]. A qualitative summary of the studies is provided in Table 3 (for detailed estimates please see Table I http://stroke.ahajournals.org). Most studies do not differentiate between ischemic and hemorrhagic stroke mortality. Several studies reported associations between short-term exposure to particle matter, including several size fractions, or gases and any stroke mortality. Only a few studies further characterized stroke into ischemic and hemorrhagic stroke mortality[24, 33–35, 38]. Short-term exposure to particulate matter and gases were associated with both ischemic stroke and hemorrhagic stroke. In Tokyo[34] the risk increase for subarachnoid hemorrhage mortality per 10 μg/m^3 $PM_{2.5}$ or NO_2 was roughly double the risk increase for ischemic or intracerebral hemorrhage mortality. It is possible that these hemorrhages may have more precise temporal relationship between air pollution exposure and the timing of stroke onset leading to less exposure misclassification and more precise estimation of the association[42]. Stronger associations between short-term air pollution exposure and stroke mortality were observed in elderly[25, 30], women[25] and individuals with a history of diabetes[41] or cardiac disease[38] in some but not all studies.

Short-term air pollution exposure and hospitalization for stroke

Studies of short-term air pollution exposure and hospitalization for any stroke have reported mixed results[43–63]. However, in contrast to studies investigating short-term exposure to air pollution and stroke mortality that typically use death certificate data, some studies of associations with hospital admissions for stroke have had more data on stroke type. These studies have reported associations between PM_{10}[45, 46, 64, 65], $PM_{2.5}$[66–68], black carbon[68], CO[51, 58, 64], NO_2[43, 58, 64, 68], and O_3[62, 69, 70] and ischemic stroke (Table 4, for detailed estimates please see Table II http://stroke.ahajournals.org). A majority did not observe associations between air pollutants and hemorrhagic stroke[45, 58, 62, 65, 69] with a few exceptions[56, 57, 63, 64, 71] including one study that specifically investigated days in Taiwan polluted by Asian dust storms originating from the Gobi desert[63]. Of the studies with specific data on subtype of ischemic stroke, PM_{10}, $PM_{2.5}$ and O_3 were associated with strokes characterized as large-artery atherosclerotic strokes, small-vessel occlusions, lacunar strokes or TIAs rather than cardioembolic strokes[46, 67–69]. Stronger associations were reported for recurrent ischemic strokes or history of stroke[58, 70], in individuals with diabetes or on diabetes medication[67, 70], and with one or more cardiovascular risk factors[69, 70]. A few studies reported stronger associations between O_3 and ischemic stroke in men than women[62, 69, 72]. Air pollution on warm days was more strongly associated with both hemorrhagic and ischemic stroke in Taiwan[64]. Associations between air pollution and ischemic stroke were stronger in the warm season in Edmonton, Canada[58] and Dijon, France[70] in contrast to Wuhan[61] where associations were stronger in the cold season. Differences may reflect better exposure classification due to time spent outdoors in climates like Edmonton, Canada but may also be due to seasonal interactions between pollutants.

Summary

The current evidence suggests exposure to higher levels of air pollutants related to combustion increases the risk of stroke. Studies of both long-term and short-term air pollution exposure suggest consistent evidence of increased risk of ischemic stroke and moderately consistent evidence supporting an association with hemorrhagic stroke. A few studies exploring susceptible subgroups have indicated stronger associations in individuals with several cardiovascular risk factors, diabetes, previous stroke and of older age. A recently published meta-analysis focusing on short-term air pollution exposure and stroke incidence or mortality reported significant associations for $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and O_3 for stroke with stronger associations for ischemic stroke[73].

Because much of the existing literature is based on linkage of administrative data, an important limitation of many available studies is limited ability to classify and validate specific stroke outcomes. Ischemic stroke and hemorrhagic stroke and their subtypes have in the majority of studies been analyzed as a combined outcome despite the clear possibility that air pollution may affect underlying pathophysiologic pathways differently. Only some have separately analyzed ischemic stroke and hemorrhagic stroke and a handful have considered subtypes of ischemic stroke or hemorrhagic stroke. Similarly only a handful used thorough chart reviews and/or adjudicated the diagnosis and onset time of stroke. This highlights the need for high-quality validated diagnostic characterization of stroke outcome in studies of air pollution. In a study of short-term air pollution exposure and stroke specifically investigating the bias introduced through misclassification of time of event of stroke found that incorrect temporal classification caused up to 66% bias towards the null[42]. This may be especially relevant in mortality studies where the date of death from death certificates is used while not accounting for the time between stroke onset and death. In studies of long-term exposure to air pollution, the ability to investigate associations with stroke is dependent on the validity and resolution of the spatial exposure assessment and the adequate control for confounders related to both air pollution at place of residence and the risk of stroke, in particular socioeconomic factors.

There is growing evidence to suggest that both accumulated exposure to higher air pollution over a period of years and higher mean levels over a period of days increase the risk of stroke. In addition to improving temporal classification of exposure by validating stroke onset time, future research efforts should be directed to careful characterization of stroke subtype because air pollution may variably affect the different pathophysiological pathways. Air pollution exposure and increased risk of stroke may represent a considerable public health problem and regulations have improved air quality in many countries in Europe and the US, resulting in greater life expectancy[74]. Yet associations with stroke have been reported at levels in compliance with current standards[16, 68] highlighting the continued importance of effective regulation and monitoring in high income countries as well as extending efforts to address regulation in low and middle income countries where levels of air pollution and prevalence of stroke are on the rise.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Sources of Funding:

This work was supported by the US Environmental Protection Agency (grants R832416, RD83479801), National Institute of Environmental Health Sciences (grant P01-ES009825), Swedish Council for Working Life and Social Research Marie Curie International Postdoctoral Fellowship Programme, the Swedish Heart-Lung Foundation, the Swedish Society of Cardiology, and the Swedish Society for Medical Research. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the Environmental Protection Agency.

References

1. Go AS, Mozaffarian D, Roger VL, Benjamin EJ, Berry JD, Borden WB, et al. Heart disease and stroke statistics--2013 update: A report from the american heart association. Circulation. 2013; 127:e6–e245. [PubMed: 23239837]

NIH-PA Author Manuscript

NIH-PA Author Manuscript

2. Brook RD, Rajagopalan S, Pope CA 3rd, Brook JR, Bhatnagar A, Diez-Roux AV, et al. Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the american heart association. Circulation. 2010; 121:2331–2378. [PubMed: 20458016]
3. Brook RD, Franklin B, Cascio W, Hong Y, Howard G, Lipsett M, et al. Air pollution and cardiovascular disease: A statement for healthcare professionals from the expert panel on population and prevention science of the american heart association. Circulation. 2004; 109:2655–2671. [PubMed: 15173049]
4. Mills NL, Tornqvist H, Robinson SD, Gonzalez MC, Soderberg S, Sandstrom T, et al. Air pollution and atherothrombosis. Inhalation toxicology. 2007; 19(Suppl 1):81–89. [PubMed: 17886055]
5. Maheswaran R, Elliott P. Stroke mortality associated with living near main roads in england and wales: A geographical study. Stroke. 2003; 34:2776–2780. [PubMed: 14615623]
6. Maheswaran R, Haining RP, Brindley P, Law J, Pearson T, Fryers PR, et al. Outdoor air pollution and stroke in sheffield, united kingdom: A small-area level geographical study. Stroke. 2005; 36:239–243. [PubMed: 15604422]
7. Hu Z, Liebens J, Rao KR. Linking stroke mortality with air pollution, income, and greenness in northwest florida: An ecological geographical study. Int J Health Geogr. 2008; 7:20. [PubMed: 18452609]
8. Andersen ZJ, Kristiansen LC, Andersen KK, Olsen TS, Hvidberg M, Jensen SS, et al. Stroke and long-term exposure to outdoor air pollution from nitrogen dioxide: A cohort study. Stroke. 2012; 43:320–325. [PubMed: 22052517]
9. Jerrett M, Burnett RT, Beckerman BS, Turner MC, Krewski D, Thurston G, et al. Spatial analysis of air pollution and mortality in california. American journal of respiratory and critical care medicine. 2013; 188:593–599. [PubMed: 23805824]
10. Lipsett MJ, Ostro BD, Reynolds P, Goldberg D, Hertz A, Jerrett M, et al. Long-term exposure to air pollution and cardiorespiratory disease in the california teachers study cohort. American journal of respiratory and critical care medicine. 2011; 184:828–835. [PubMed: 21700913]
11. Miller KA, Siscovick DS, Sheppard L, Shepherd K, Sullivan JH, Anderson GL, et al. Long-term exposure to air pollution and incidence of cardiovascular events in women. The New England journal of medicine. 2007; 356:447–458. [PubMed: 17267905]
12. Ueda K, Nagasawa SY, Nitta H, Miura K, Ueshima H. Exposure to particulate matter and long-term risk of cardiovascular mortality in japan: Nippon data80. J Atheroscler Thromb. 2012; 19:246–254. [PubMed: 22075540]
13. Yorifuji T, Kashima S, Tsuda T, Ishikawa-Takata K, Ohta T, Tsuruta K, et al. Long-term exposure to traffic-related air pollution and the risk of death from hemorrhagic stroke and lung cancer in shizuoka, japan. The Science of the total environment. 2013; 443:397–402. [PubMed: 23208275]
14. Atkinson RW, Carey IM, Kent AJ, van Staa TP, Anderson HR, Cook DG. Long-term exposure to outdoor air pollution and incidence of cardiovascular diseases. Epidemiology. 2013; 24:44–53. [PubMed: 23222514]
15. Maheswaran R, Pearson T, Smeeton NC, Beevers SD, Campbell MJ, Wolfe CD. Outdoor air pollution and incidence of ischemic and hemorrhagic stroke: A small-area level ecological study. Stroke. 2012; 43:22–27. [PubMed: 22033998]
16. Stafoggia M, Cesaroni G, Peters A, Andersen ZJ, Badaloni C, Beelen R, et al. Long-term exposure to ambient air pollution and incidence of cerebrovascular events: Results from 11 european cohorts within the escape project. Environmental health perspectives. 2014; 122:919–925. [PubMed: 24835336]
17. Oudin A, Stroh E, Stromberg U, Jakobsson K, Bjork J. Long-term exposure to air pollution and hospital admissions for ischemic stroke. A register-based case-control study using modelled no(x) as exposure proxy. BMC Public Health. 2009; 9:301. [PubMed: 19691845]
18. Oudin A, Stromberg U, Jakobsson K, Stroh E, Lindgren AG, Norrving B, et al. Hospital admissions for ischemic stroke: Does long-term exposure to air pollution interact with major risk factors? Cerebrovasc Dis. 2011; 31:284–293. [PubMed: 21196728]
19. Johnson JY, Rowe BH, Villeneuve PJ. Ecological analysis of long-term exposure to ambient air pollution and the incidence of stroke in edmonton, alberta, canada. Stroke. 2010; 41:1319–1325. [PubMed: 20538697]

20. Sorensen M, Luhdorf P, Ketzel M, Andersen ZJ, Tjonneland A, Overvad K, et al. Combined effects of road traffic noise and ambient air pollution in relation to risk for stroke? Environmental research. 2014; 133C:49–55. [PubMed: 24906068]
21. Johnson JY, Rowe BH, Allen RW, Peters PA, Villeneuve PJ. A case-control study of medium-term exposure to ambient nitrogen dioxide pollution and hospitalization for stroke. BMC Public Health. 2013; 13:368. [PubMed: 23597019]
22. Chen R, Zhang Y, Yang C, Zhao Z, Xu X, Kan H. Acute effect of ambient air pollution on stroke mortality in the china air pollution and health effects study. Stroke. 2013; 44:954–960. [PubMed: 23391765]
23. Hoek G, Brunekreef B, Fischer P, van Wijnen J. The association between air pollution and heart failure, arrhythmia, embolism, thrombosis, and other cardiovascular causes of death in a time series study. Epidemiology. 2001; 12:355–357. [PubMed: 11337606]
24. Hong YC, Lee JT, Kim H, Kwon HJ. Air pollution: A new risk factor in ischemic stroke mortality. Stroke. 2002; 33:2165–2169. [PubMed: 12215581]
25. Hong YC, Lee JT, Kim H, Ha EH, Schwartz J, Christiani DC. Effects of air pollutants on acute stroke mortality. Environmental health perspectives. 2002; 110:187–191. [PubMed: 11836148]
26. Kan H, Jia J, Chen B. Acute stroke mortality and air pollution: New evidence from shanghai, china. J Occup Health. 2003; 45:321–323. [PubMed: 14646274]
27. Kettunen J, Lanki T, Tiittanen P, Aalto PP, Koskentalo T, Kulmala M, et al. Associations of fine and ultrafine particulate air pollution with stroke mortality in an area of low air pollution levels. Stroke. 2007; 38:918–922. [PubMed: 17303767]
28. Li G, Zhou M, Cai Y, Zhang Y, Pan X. Does temperature enhance acute mortality effects of ambient particle pollution in tianjin city, china. The Science of the total environment. 2011; 409:1811–1817. [PubMed: 21376370]
29. Qian Z, He Q, Lin HM, Kong L, Liao D, Dan J, et al. Association of daily cause-specific mortality with ambient particle air pollution in wuhan, china. Environmental research. 2007; 105:380–389. [PubMed: 17604019]
30. Qian Z, He Q, Lin HM, Kong L, Liao D, Yang N, et al. Short-term effects of gaseous pollutants on cause-specific mortality in wuhan, china. J Air Waste Manag Assoc. 2007; 57:785–793. [PubMed: 17687993]
31. Qian Z, He Q, Lin HM, Kong L, Bentley CM, Liu W, et al. High temperatures enhanced acute mortality effects of ambient particle pollution in the "oven" city of wuhan, china. Environmental health perspectives. 2008; 116:1172–1178. [PubMed: 18795159]
32. Qian Z, Lin HM, Stewart WF, Kong L, Xu F, Zhou D, et al. Seasonal pattern of the acute mortality effects of air pollution. J Air Waste Manag Assoc. 2010; 60:481–488. [PubMed: 20437783]
33. Turin TC, Kita Y, Rumana N, Nakamura Y, Ueda K, Takashima N, et al. Ambient air pollutants and acute case-fatality of cerebro-cardiovascular events: Takashima stroke and ami registry, japan (1988–2004). Cerebrovasc Dis. 2012; 34:130–139. [PubMed: 22868897]
34. Yorifuji T, Kawachi I, Sakamoto T, Doi H. Associations of outdoor air pollution with hemorrhagic stroke mortality. J Occup Environ Med. 2011; 53:124–126. [PubMed: 21270652]
35. Yorifuji T, Kashima S. Associations of particulate matter with stroke mortality: A multicity study in japan. J Occup Environ Med. 2013; 55:768–771. [PubMed: 23787566]
36. Zanobetti A, Schwartz J. The effect of fine and coarse particulate air pollution on mortality: A national analysis. Environmental health perspectives. 2009; 117:898–903. [PubMed: 19590680]
37. Maynard D, Coull BA, Gryparis A, Schwartz J. Mortality risk associated with short-term exposure to traffic particles and sulfates. Environmental health perspectives. 2007; 115:751–755. [PubMed: 17520063]
38. Qian Y, Zhu M, Cai B, Yang Q, Kan H, Song G, et al. Epidemiological evidence on association between ambient air pollution and stroke mortality. J Epidemiol Community Health. 2013; 67:635–640. [PubMed: 23661720]
39. Ren C, Melly S, Schwartz J. Modifiers of short-term effects of ozone on mortality in eastern massachusetts--a case-crossover analysis at individual level. Environmental health : a global access science source. 2010; 9:3. [PubMed: 20092648]

40. Zeka A, Zanobetti A, Schwartz J. Short term effects of particulate matter on cause specific mortality: Effects of lags and modification by city characteristics. Occup Environ Med. 2005; 62:718–725. [PubMed: 16169918]
41. Zeka A, Zanobetti A, Schwartz J. Individual-level modifiers of the effects of particulate matter on daily mortality. American journal of epidemiology. 2006; 163:849–859. [PubMed: 16554348]
42. Lokken RP, Wellenius GA, Coull BA, Burger MR, Schlaug G, Suh HH, et al. Air pollution and risk of stroke: Underestimation of effect due to misclassification of time of event onset. Epidemiology. 2009; 20:137–142. [PubMed: 19244659]
43. Ballester F, Tenias JM, Perez-Hoyos S. Air pollution and emergency hospital admissions for cardiovascular diseases in valencia, spain. J Epidemiol Community Health. 2001; 55:57–65. [PubMed: 11112952]
44. Burnett RT, Smith-Doiron M, Stieb D, Cakmak S, Brook JR. Effects of particulate and gaseous air pollution on cardiorespiratory hospitalizations. Arch Environ Health. 1999; 54:130–139. [PubMed: 10094292]
45. Chan CC, Chuang KJ, Chien LC, Chen WJ, Chang WT. Urban air pollution and emergency admissions for cerebrovascular diseases in taipei, taiwan. Eur Heart J. 2006; 27:1238–1244. [PubMed: 16537554]
46. Corea F, Silvestrelli G, Baccarelli A, Giua A, Previdi P, Siliprandi G, et al. Airborne pollutants and lacunar stroke: A case cross-over analysis on stroke unit admissions. Neurol Int. 2012; 4:e11. [PubMed: 23139849]
47. Jalaludin B, Morgan G, Lincoln D, Sheppeard V, Simpson R, Corbett S. Associations between ambient air pollution and daily emergency department attendances for cardiovascular disease in the elderly (65+ years), sydney, australia. Journal of exposure science & environmental epidemiology. 2006; 16:225–237. [PubMed: 16118657]
48. Larrieu S, Jusot JF, Blanchard M, Prouvost H, Declercq C, Fabre P, et al. Short term effects of air pollution on hospitalizations for cardiovascular diseases in eight french cities: The psas program. The Science of the total environment. 2007; 387:105–112. [PubMed: 17727917]
49. Le Tertre A, Medina S, Samoli E, Forsberg B, Michelozzi P, Boumghar A, et al. Short-term effects of particulate air pollution on cardiovascular diseases in eight european cities. J Epidemiol Community Health. 2002; 56:773–779. [PubMed: 12239204]
50. Linn WS, Szlachcic Y, Gong H Jr, Kinney PL, Berhane KT. Air pollution and daily hospital admissions in metropolitan los angeles. Environmental health perspectives. 2000; 108:427–434. [PubMed: 10811569]
51. Moolgavkar SH. Air pollution and hospital admissions for diseases of the circulatory system in three u.S. Metropolitan areas. J Air Waste Manag Assoc. 2000; 50:1199–1206. [PubMed: 10939212]
52. Nascimento LF, Francisco JB, Patto MB, Antunes AM. Environmental pollutants and stroke-related hospital admissions. Cad Saude Publica. 2012; 28:1319–1324. [PubMed: 22729262]
53. Poloniecki JD, Atkinson RW, de Leon AP, Anderson HR. Daily time series for cardiovascular hospital admissions and previous day's air pollution in london, uk. Occup Environ Med. 1997; 54:535–540. [PubMed: 9326156]
54. Ponka A, Virtanen M. Low-level air pollution and hospital admissions for cardiac and cerebrovascular diseases in helsinki. Am J Public Health. 1996; 86:1273–1280. [PubMed: 8806380]
55. Sunyer J, Ballester F, Tertre AL, Atkinson R, Ayres JG, Forastiere F, et al. The association of daily sulfur dioxide air pollution levels with hospital admissions for cardiovascular diseases in europe (the aphea-ii study). Eur Heart J. 2003; 24:752–760. [PubMed: 12713769]
56. Turin TC, Kita Y, Rumana N, Nakamura Y, Ueda K, Takashima N, et al. Short-term exposure to air pollution and incidence of stroke and acute myocardial infarction in a japanese population. Neuroepidemiology. 2012; 38:84–92. [PubMed: 22338644]
57. Villeneuve PJ, Chen L, Stieb D, Rowe BH. Associations between outdoor air pollution and emergency department visits for stroke in edmonton, canada. European journal of epidemiology. 2006; 21:689–700. [PubMed: 17048082]

58. Villeneuve PJ, Johnson JY, Pasichnyk D, Lowes J, Kirkland S, Rowe BH. Short-term effects of ambient air pollution on stroke: Who is most vulnerable? The Science of the total environment. 2012; 430:193–201. [PubMed: 22647242]

59. Wong TW, Lau TS, Yu TS, Neller A, Wong SL, Tam W, et al. Air pollution and hospital admissions for respiratory and cardiovascular diseases in hong kong. Occup Environ Med. 1999; 56:679–683. [PubMed: 10658547]

60. Wordley J, Walters S, Ayres JG. Short term variations in hospital admissions and mortality and particulate air pollution. Occup Environ Med. 1997; 54:108–116. [PubMed: 9072018]

61. Xiang H, Mertz KJ, Arena VC, Brink LL, Xu X, Bi Y, et al. Estimation of short-term effects of air pollution on stroke hospital admissions in wuhan, china. PloS one. 2013; 8:e61168. [PubMed: 23593421]

62. Xu X, Sun Y, Ha S, Talbott EO, Lissaker CT. Association between ozone exposure and onset of stroke in allegheny county, pennsylvania, USA, 1994–2000. Neuroepidemiology. 2013; 41:2–6. [PubMed: 23548644]

63. Yang CY, Chen YS, Chiu HF, Goggins WB. Effects of asian dust storm events on daily stroke admissions in taipei, taiwan. Environmental research. 2005; 99:79–84. [PubMed: 16053931]

64. Tsai SS, Goggins WB, Chiu HF, Yang CY. Evidence for an association between air pollution and daily stroke admissions in kaohsiung, taiwan. Stroke. 2003; 34:2612–2616. [PubMed: 14551399]

65. Wellenius GA, Schwartz J, Mittleman MA. Air pollution and hospital admissions for ischemic and hemorrhagic stroke among medicare beneficiaries. Stroke. 2005; 36:2549–2553. [PubMed: 16254223]

66. Lisabeth LD, Escobar JD, Dvonch JT, Sanchez BN, Majersik JJ, Brown DL, et al. Ambient air pollution and risk for ischemic stroke and transient ischemic attack. Ann Neurol. 2008; 64:53–59. [PubMed: 18508356]

67. O'Donnell MJ, Fang J, Mittleman MA, Kapral MK, Wellenius GA. Fine particulate air pollution (pm2.5) and the risk of acute ischemic stroke. Epidemiology. 2011; 22:422–431. [PubMed: 21399501]

68. Wellenius GA, Burger MR, Coull BA, Schwartz J, Suh HH, Koutrakis P, et al. Ambient air pollution and the risk of acute ischemic stroke. Archives of internal medicine. 2012; 172:229–234. [PubMed: 22332153]

69. Henrotin JB, Besancenot JP, Bejot Y, Giroud M. Short-term effects of ozone air pollution on ischaemic stroke occurrence: A case-crossover analysis from a 10-year population-based study in dijon, france. Occup Environ Med. 2007; 64:439–445. [PubMed: 17409181]

70. Henrotin JB, Zeller M, Lorgis L, Cottin Y, Giroud M, Bejot Y. Evidence of the role of short-term exposure to ozone on ischaemic cerebral and cardiac events: The dijon vascular project (diva). Heart. 2010; 96:1990–1996. [PubMed: 20702540]

71. Yamazaki S, Nitta H, Ono M, Green J, Fukuhara S. Intracerebral haemorrhage associated with hourly concentration of ambient particulate matter: Case-crossover analysis. Occup Environ Med. 2007; 64:17–24. [PubMed: 16847037]

72. Bedada GB, Smith CJ, Tyrrell PJ, Hirst AA, Agius R. Short-term effects of ambient particulates and gaseous pollutants on the incidence of transient ischaemic attack and minor stroke: A case-crossover study. Environmental health : a global access science source. 2012; 11:77. [PubMed: 23067103]

73. Yang WS, Wang X, Deng Q, Fan WY, Wang WY. An evidence-based appraisal of global association between air pollution and risk of stroke. International journal of cardiology. 2014; 175:307–313. [PubMed: 24866079]

74. Pope CA 3rd, Ezzati M, Dockery DW. Fine-particulate air pollution and life expectancy in the united states. The New England journal of medicine. 2009; 360:376–386. [PubMed: 19164188]

Table 1

Studies of Long-term Air Pollution Exposure and Stroke Mortality

Study	Location	Study Design	Stroke Outcome	Relative risk (95% Confidence Intervals)	Exposure
Maheswaran 2003[5]	England and Wales	Ecological	Any stroke	1.05 (1.04, 1.07)	living within 200m of main road compared to ≥1000m
Maheswaran 2005[6]	Sheffield, UK	Ecological	Any stroke	1.37 (1.19, 1.57) PM_{10} 1.26 (1.10, 1.46) CO 1.33 (1.14, 1.56) NO_x	highest to lowest quintile of modelled pollutant
Hu 2008[7]	Florida, USA	Ecological	Any stroke	1.09 (1.03, 1.15)*	per 10,000 vehicles/day within census tract
Andersen 2012[8]	Denmark	Cohort	Any stroke Ischemic Hemorrhagic	1.22 (1.00, 1.50) 1.46 (0.90, 2.39) 1.00 (0.76, 1.31)	per interquartile range increase (43%) in mean modeled NO_2 since 1971
Jerrett 2013[9]	California, USA	Cohort	Any stroke	1.07 (0.99, 1.15) $PM_{2.5}$ 1.08 (1.02, 1.15) NO_2 1.01 (0.92, 1.11) O_3	per 5.3 μg/m^3 $PM_{2.5}$ per 4.12 ppb NO_2 per 24.2 ppb O_3
Lipsett 2011[10]	California, USA	Cohort	Any stroke	0.99 (0.89, 1.09) PM_{10} 1.16 (0.92, 1.46) $PM_{2.5}$	per 10 μg/m^3 mean PM_{10} 1996–2005, or mean $PM_{2.5}$ 1999–2005
Miller 2007[11]	36 US cities	Cohort	Any stroke	1.83 (1.11, 3.00) $PM_{2.5}$	annual mean in 2000 at closest monitor per 10 μg/m^3
Ueda 2012[12]	Japan	Cohort	Any stroke	0.86 (0.74, 1.01) PM_{10}	per 10 μg/m^3 annual mean at closest monitor
Yorifuji 2013[13]	Shizuoka, Japan	Cohort	Any stroke Ischemic Hemorrhagic	1.19 (1.06, 1.34) 1.20 (1.04, 1.39) 1.28 (1.05, 1.57)	per 10 μg/m^3 annual mean NO_2

*95% Credible interval from a Bayesian analysis

Abbreviatons: CO, Carbon monoxide. NO_2, Nitrogen dioxide. NO_x, Nitrogen oxides. O_3, Ozone. PM_{10}, Particles with aerodynamic diameter ≤ 10μm. $PM_{2.5}$, Fine particles with aerodynamic diameter≤ 2.5μm.

Table 2

Studies of Long-term Air Pollution Exposure and Hospitalization for Stroke

Study	Location	Study Design	Stroke Outcome	Relative Risk (95% Confidence Intervals)	Exposure
Maheswaran 2005[6]	Sheffield, UK	Ecological	Any stroke	1.13 (0.99, 1.29) PM_{10} 1.11 (0.99, 1.25) CO 1.13 (1.04, 1.27) NO_x	highest to lowest quintile of modelled pollutant
Andersen 2012[8]	Denmark	Cohort	Any stroke Ischemic Hemorrhagic	1.05 (0.99, 1.11) 1.05 (0.95, 1.17 0.93 (0.81, 1.07)	per interquartile range increase (43%) in mean modeled NO_2 since 1971
Lipsett 2011[10]	California	Cohort	Any stroke	1.06 (1.00, 1.13) PM_{10} 1.14 (0.99, 1.32) $PM_{2.5}$	per 10 μg/m^3 annual mean pollutant at closest monitor
Miller 2007[11]	36 US cities	Cohort	Any stroke	1.28 (1.01, 1.61) $PM_{2.5}$	per 10 μg/m^3 mean of closest monitor during 2000
Maheswaran 2012[15]	London, UK	Ecological	Ischemic Hemorrhagic	1.22 (0.77, 1.93) PM_{10} 1.11 (0.93, 1.32) NO_2 0.52 (0.20, 1.37) PM_{10} 0.86 (0.60, 1.24) NO_2	per 10 μg/m^3 of modelled pollutant exposure
Atkinson 2013[14]	England	Cohort	Any stroke	0.98 (0.95, 1.01) PM_{10} 0.99 (0.95, 1.03) NO_2 1.02 (1.00, 1.05) SO_2 1.00 (0.97, 1.04) O_3	per 3.0 μg/m^3 PM_{10} per 10.7 μg/m^3 NO_2 per 2.2 μg/m^3 SO_2 per 3.0 μg/m^3 O_3 modelled annual mean
Stafoggia 2014[16]	11 cohorts, Europe	Cohort	Any stroke	1.19 (0.88, 1.62)	per 5 μg/m^3 annual mean $PM_{2.5}$
Oudin 2009[17]	Scania, Sweden	Case-control	Ischemic	0.95 (0.86, 1.06)	annual mean modelled NO_x of 20–30 μg/m^3 vs <10 μg/m^3
Oudin 2011[18]	Scania, Sweden	Case-control	Ischemic	In diabetics: 2.0 (1.2, 3.4) high NO_x 1.3 (1.1, 1.6) low NO_x	Modelled annual NO_x High NO_x ≥25 μg/m^3 Low NO_x <15 μg/m^3 Reference: non-diabetics with low NO_x
Johnson 2010[19]	Edmonton, Canada	Ecological	Any stroke Nonhemorrhagic Hemorrhagic	1.29 (1.16, 1.43) 1.36 (1.19,1.56) 1.46 (1.19, 1.80)	highest (16.7–20.3 ppb) to lowest quintile (10.1–14.0 ppb) of NO_2 exposure
Sørensen 2014[20]	Denmark	Cohort	Any stroke Ischemic Hemorrhagic	1.08 (1.01, 1.16) 1.11 (1.03, 1.20) 1.00 (0.80, 1.24)	per 10 μg/m^3 annual mean NO_2

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Study	Location	Study Design	Stroke Outcome	Relative Risk (95% Confidence Intervals)	Exposure
Johnson 2013[21]	Edmonton, Canada	Case-control	Any stroke	1.01 (0.94, 1.08)	per 5 ppb NO_2
			Ischemic	1.03 (0.94, 1.13)	
			TIA	0.95 (0.86, 1.05)	
			Hemorrhagic	1.07 (0.92, 1.24)	

Abbreviatons: CO, Carbon monoxide. NO_2, Nitrogen dioxide. NO_x, Nitrogen oxides. O_3, Ozone. PM_{10}, Particles with aerodynamic diameter ≤ 10µm. $PM_{2.5}$, Fine particles with aerodynamic diameter≤ 2.5µm. SO_2, Sulfur dioxide.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 3

Studies of Short-term Air Pollution Exposure and Stroke Mortality

Study	Location	Study Design	Stroke Outcome	Positive associations*	Null associations†
Chen 2013[22]	8 Chinese cities	Time-series	Any stroke	PM_{10}, NO_2, SO_2	
Hoek 2001[23]	Netherlands	Time-series	Any stroke	Black smoke, CO, SO_2, and O_3.	PM_{10} and NO_2
Hong 2002[24]	Seoul, Korea	Time-series	Ischemic Hemorrhagic	TSP, CO, NO_2, SO_2, O_3 TSP	CO, NO_2, SO_2, O_3
Hong 2002[25]	Seoul, Korea	Time-series	Any stroke	PM_{10}, CO, NO_2, SO_2, O_3	
Kan 2003[26]	Shanghai, China	Time-series	Any stroke	PM_{10}, NO_2	SO_2
Kettunen 2007[27]	Helsinki, Finland	Time-series	Any stroke	$PM_{2.5}$, CO in warm season	PM_{10}, Coarse PM, $PM_{0.1}$, NO_2, O_3 in warm season. No associations in cold season.
Li 2011[28]	Tianjin, Taiwan	Time-series	Any stroke	PM_{10} on days with >20°C	PM_{10} on days with ≤ 20°C
Qian 2007[29]	Wuhan, China	Time-series	Any stroke	PM_{10}	
Qian 2007[30]	Wuhan, China	Time-series	Any stroke	NO_2	SO_2, O_3
Qian 2008[31]	Wuhan, China	Time-series	Any stroke	PM_{10} all days and NO_2, SO_2 on normal temperature days	O_3 all days and NO_2, SO_2 on high temperature days
Qian 2010[32]	Wuhan, China	Time-series	Any stroke	NO_2 in spring. PM_{10}, NO_2, SO_2 in winter.	PM_{10} and SO_2 in spring. All pollutants summer or fall.
Turin 2012[33]	Takashima, Japan	Time-series	Any stroke Ischemic Hemorrhagic	NO_2	Suspended PM, NO_2, SO_2, O_3 Suspended PM, SO_2, O_3 Suspended PM, NO_2, SO_2, O_3
Yorifuji 2011[34]	Tokyo, Japan	Time-series	Any stroke Ischemic Hemorrhagic	$PM_{2.5}$, NO_2 $PM_{2.5}$, NO_2	$PM_{2.5}$, NO_2
Yorifuji 2013[35]	47 Japanese cities	Time-series	Any stroke Ischemic Hemorrhagic	PM_{10}	PM_{10} PM_{10}
Zanobetti 2009[36]	112 US cities	Time-series	Any stroke	$PM_{2.5}$, PM_{coarse}	
Maynard 2007[37]	Massachusetts, USA	Case-crossover	Any stroke	Black carbon	SO_4
Qian 2013[38]	Shanghai, China	Case-crossover	Any stroke Ischemic Hemorrhagic	PM_{10}, NO_2, SO_2 PM_{10}, NO_2, SO_2 NO_2, SO_2	PM_{10}

Study	Location	Study Design	Stroke Outcome	Positive associations*	Null associations†
Ren 2010[39]	Massachusetts, USA	Case-crossover	Any stroke	O_3	
Zeka 2005[40]	20 US cities	Case-crossover	Any stroke	PM_{10}	
Zeka 2006[41]	20 US cities	Case-crossover	Any stroke	PM_{10} if pneumonia or ≥75 years old	PM_{10} if no pneumonia or ≤75 years old

*Positive associations with confidence intervals not including the null.

†Associations with confidence intervals including the null.

Abbreviatons: CO, Carbon monoxide. NO_2, Nitrogen dioxide. O_3, Ozone. PM_{10}, Particles with aerodynamic diameter ≤ 10μm. $PM_{2.5}$, Fine particles with aerodynamic diameter≤ 2.5μm. PM_{coarse}, Coarse particles with aerodynamic diameter between 2.5 and 10 μm in aerodynamic diameter. $PM_{0.1}$, Ultrafine particles with less than 0.1 μm aerodynamic diameter. SO_2, Sulfur dioxide. SO_4, Sulfate. TSP, Total suspended particles.

Table 4

Studies of Short-term Exposure to Air Pollution and Hospital Admissions for Stroke

Study	Location	Study Design	Stroke Outcome	Positive associations*	Null Associations†
Ballester 2001[43]	Valencia, Spain	Time-series	Any stroke	NO_2	CO, SO_2, O_3
Burnett 1999[44]	Toronto, Canada	Time-series	Any stroke		PM_{10}, CO, NO_2, O_3
Chan 2006[45]	Taipei, Taiwan	Time-series	Any stroke Ischemic Hemorrhagic	PM_{10}, $PM_{2.5}$, O_3	CO, NO_2, SO_2 PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, O_3 PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, O_3
Corea 2012[46]	Mantua, Italy	Case-crossover	Any stroke Ischemic	PM10 PM_{10} in all ischemic, large vessel, small vessel, and lacunar	PM_{10} in cardioembolic. CO, NO_2, SO_2, O_3.
Jalaludin 2006[47]	Sydney, Australia	Time-series	Any stroke		PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, O_3
Larrieu 2007[48]	8 French cities	Time-series	Any stroke		PM_{10}, NO_2, O_3
Le Tertre 2002[49]	8 European cities	Time-series	Any stroke		PM_{10}, black smoke
Linn 2000[50]	Los Angeles, USA	Time-series	Any stroke	CO, NO_2 in spring	PM_{10}, O_3
Moolgavkar 2000[51]	Los Angeles, USA	Time-series	Any stroke	PM_{10}, CO, NO_2, SO_2	$PM_{2.5}$
Nascimento 2012[52]	Sao Jose Campos, Brazil	Time-series	Any stroke	PM_{10}, SO_2	O_3
Poloniecki 1997[53]	London, UK	Time-series	Any stroke		Black smoke, CO, NO_2, SO_2, O_3
Pönkä 1996[54]	Helsinki, Finland	Time-series	Any stroke Ischemic	NO_2 Total suspended particles	
Sunyer 2003[55]	7 European cities	Time-series	Any stroke		SO_2
Turin 2012[56]	Takashima, Japan	Time-series	Any stroke Ischemic Hemorrhagic	 SO_2	PM_{10},NO_2, SO_2, O_3 PM_{10},NO_2, SO_2, O_3 PM_{10},NO_2, O_3
Villeneuve 2006[57]	Edmonton, Canada	Case-crossover	Any stroke Ischemic TIA Hemorrhagic	$PM_{2.5}$ SO_2	PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, O_3 CO, NO_2, SO_2, O_3 PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, O_3

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Study	Location	Study Design	Stroke Outcome	Positive associations*	Null Associations†
					PM_{10}, $PM_{2.5}$, CO, NO_2, O_3
Villeneuve 2012[58]	Edmonton, Canada	Case-crossover	Any stroke Ischemic Hemorrhagic	CO in warm season CO, NO_2,O_3 in warm season	$PM_{2.5}$, NO_2, SO_2, O_3. CO all year. $PM_{2.5}$, NO_2, SO_2, O_3. CO all year. $PM_{2.5}$, CO, NO_2, SO_2, O_3
Wong 1999[59]	Hong Kong, China	Time-series	Any stroke		PM_{10}, NO_2, SO_2, O_3
Wordley 1997[60]	Birmingham, UK	Time-series	Any stroke	PM_{10}	
Xiang 2013[61]	Wuhan, China	Case-crossover	Any stroke	PM_{10}, NO_2 in cold season	PM_{10}, NO_2 SO_2 all year and in subtypes. PM_{10}, NO_2 in warm season.
Xu 2013[62]	Allegheny, USA	Case-crossover	Any stroke Ischemic Hemorrhagic	O_3 O_3	O_3
Yang 2005[63]	Taipei,Taiwan	Time-series	Any stroke Ischemic TIA Hemorrhagic	Asian dust and intracerebral	Asian dust Asian dust Asian dust and subarachnoidal
Tsai 2003[64]	Kaoshiung, Taiwan	Case-crossover	Ischemic Hemorrhagic	PM_{10}, NO_2, SO_2, O_3 warm days, CO all days PM_{10}, CO, NO_2, O_3 warm days	PM_{10}, NO_2, SO_2, O_3 cool days SO_2 warm days, All pollutants cool days
Wellenius 2005[65]	9 US cities	Case-crossover	Ischemic Hemorrhagic	PM_{10}, CO, NO_2, SO_2	PM_{10}, CO, NO_2, SO_2
Lisabeth 2008[66]	Corpus Christi, USA	Time-series	Ischemic	$PM_{2.5}$	O_3
O'Donnell 2011[67]	8 Canadian cities	Case-crossover	Ischemic	$PM_{2.5}$ in diabetics and non-cardioembolic	$PM_{2.5}$ in ischemic strokes overall
Wellenius 2012[68]	Boston, USA	Case-crossover	Ischemic	$PM_{2.5}$, black carbon, NO_2. $PM_{2.5}$ large and small vessel stroke	CO, SO_4, O_3. $PM_{2.5}$cardioembolic stroke
Henrotin 2007[69]	Dijon, France	Case-crossover	Ischemic Hemorrhagic	O_3 in all ischemic, large vessel, and TIA	PM_{10}, CO, NO_2, SO_2 PM_{10}, CO, NO_2, SO_2, O_3
Henrotin 2010[70]	Dijon, France	Case-crossover	Ischemic	O_3 in recurrent stroke	O_3 in recurrent stroke
Yamazaki 2007[71]	Japan	Case-crossover	Ischemic	PM_7 2h before intracerebral hemorrhage	PM_7, NO_2, O_3 in 24h averages
Bedada 2012[72]	UK	Case-crossover	Minor stroke	NO	CO, NO_2, SO_2, O_3

* Positive associations with confidence intervals not including the null.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

† Associations with confidence interval sincluding the null.

Abbreviatons: BC, Black carbon. BS, Black smoke. CI, Confidence intervals. CO, Carbon monoxide. H, hour.Max, Daily maximum.NO, Nitric oxide. NO_2, Nitrogen dioxide. NS, Non-significant associations but estimates not provided in publication. O_3, Ozone. PM_{10}, Particles with aerodynamic diameter ≤ 10μm. $PM_{2.5}$, Fine particles with aerodynamic diameter ≤ 2.5μm. PM_{coarse}, Coarse particles with aerodynamic diameter between 2.5 and 10 μm in aerodynamic diameter. $PM_{0.1}$, Ultrafine particles with less than 0.1 μm aerodynamic diameter. SO_2, Sulfur dioxide. SO_4, Sulfate. TSP, Total suspended particles.